

Enhancing Agricultural Resource Management through Electrical Optimization of a Solar-Powered Irrigation System with Soil Moisture Sensor

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ABSTRACT

This study assessed the performance, sustainability, and effectiveness of a 300-watt (300W) solar-powered irrigation system (SPIS) implemented in Tabuyuc, Apalit, Pampanga. The system, consisting of a 300W solar panel, a 24-volt (24V), 50-ampere-hour (50Ah) lead-acid battery, and automatic soil moisture sensors, provided reliable energy for irrigation, with energy generation ranging from 440.64 watt-hours (Wh) to 1366.33 Wh. Despite high energy consumption on April 19, the system continued operating without interruptions, demonstrating resilience under increased demand. Battery performance data revealed efficient voltage recovery, with peak discharges managed effectively, and the system consistently recharged during the day. The SPIS significantly reduced water consumption, using only 161.2 liters per session compared to 1,680 liters with conventional irrigation, saving over 90% of water. The automated system precisely controlled water application, minimizing waste and ensuring efficient irrigation. Economically, the SPIS proved cost-effective, with estimated monthly savings of ₱1,260 and a payback period of 1.8 years. The findings suggest that increasing battery capacity and adding multi-point moisture sensors could enhance performance, especially for larger plots. Further field testing under harsh conditions is recommended to assess the system's durability. Collaboration with agricultural programs and rural development initiatives could promote wider adoption, positioning the SPIS as a scalable solution for sustainable farming in off-grid areas, enhancing water and energy efficiency.

Keywords: Solar-Powered Irrigation System (SPIS); Sustainable Agriculture; Water Efficiency; Energy Efficiency; Soil Moisture Sensor; Off-Grid Farming; Battery Performance; Renewable Energy; Irrigation Automation; Payback Period; Rural Development.

1. Introduction

Agriculture remains vital to economic development and food security, but is increasingly challenged by climate change, population growth, and unsustainable resource use [32],[27]. Efficient irrigation has emerged as a key strategy for addressing these issues, particularly through the integration of renewable energy and automation technologies [43]. Traditional irrigation systems, though widely used in the Philippines for their affordability, often lead to inefficient water use and inconsistent crop yields [23]. In contrast, solar-powered irrigation systems (SPIS), especially when paired with soil moisture sensors, offer a sustainable alternative by automating water delivery based on real-time soil data. This improves water-use efficiency, reduces energy consumption, and enhances crop health [23].

Sprinkler irrigation systems are especially effective, as they mimic natural rainfall, provide uniform water distribution, and suit a variety of soil types and crop densities [5]. Recent local implementations, such as a 550W solar-powered sprinkler system in Bacolor, Pampanga, demonstrate the practicality and sustainability of such systems in small-scale farms [11]. However, adoption barriers remain, including high initial costs and the need for technical skills. Despite these, the integration of smart irrigation technologies is shown to significantly improve water conservation and crop productivity [28].

This study explores the optimization of a solar-powered sprinkler irrigation system with integrated soil moisture sensors, using Green Ice lettuce as the test crop. Due to its sensitivity to moisture and commercial value, lettuce serves as an ideal model to evaluate irrigation efficiency. The findings aim to contribute to sustainable agriculture

by demonstrating how energy-efficient, sensor-based irrigation can reduce water waste, support renewable energy use, and promote resilient agricultural practices in the face of growing global food demands.

1.1. Study Objectives

The objectives of this study are as follows:

- (1) To assess the performance and energy utilization of the system's electrical components, including solar panels and batteries, by measuring their output, energy consumption, and overall contribution to the operation of the solar-powered irrigation system.
- (2) To evaluate the potential of solar-powered irrigation systems to reduce water waste in Tabuyuc, Apalit, Pampanga, by comparing the water usage of solar-powered systems against conventional irrigation methods.
- (3) To assess the effectiveness of integrating soil moisture sensors into solar-powered irrigation systems in optimizing irrigation scheduling and maintaining consistent soil moisture levels compared to traditional irrigation systems.
- (4) To evaluate the economic viability of a solar-powered irrigation system with soil moisture sensors by computing its payback period and return on investment.

2. Methods

This section outlines the systematic process undertaken in the development and evaluation of the solar-powered irrigation system. The methodology covers the determination of discharge or flow rate through the bucket method, assessment of the system's reliability, selection and procurement of electrical and irrigation 4 method was used to determine the flow rate of the irrigation system. A 16-liter container and a stopwatch were used to measure the time it took to fill the container from the pump's discharge. The flow was fully diverted into the container to ensure accuracy [43],[31]. The flow rate was calculated using:

$$Q = \frac{V}{t} \quad \dots(1)$$

where Q is the flow rate (L/min), V is volume, and t is time. The test was repeated five times, and the average time was used. While simple and effective for small, steady flows, accuracy may be affected by flow variations and environmental conditions [20],[31].

2.1. Selection and Identification of Materials

The selection of the appropriate materials was essential in this study as this would shape the whole setup of the system and how the prototype was built.

2.1.1. Motor

Hydraulic power refers to the rate at which energy is transferred through a moving fluid. It takes into account the fluid's density, flow rate, elevation difference (head), gravitational acceleration, and system efficiency. The equation used is:

$$P_R = Q \times \rho \times g \times h_T \quad \dots(2)$$

where P is power (W), ρ is fluid density (kg/m^3), Q is flow rate (m^3/s), g is gravity (9.81 m/s^2), h is head (m), and η is efficiency [31]. This formula provides a basis for estimating energy transfer in fluid systems and evaluating overall system performance [31].

2.1.2. PV/Solar Panels

To estimate the total energy requirement of the solar-powered irrigation system, the individual energy consumption of each electrical component—including the pump, valve, motor, and Arduino—was calculated and summed to determine overall system demand over a specific period:

$$E_x = \text{Prequired (W)} \times \text{Operating Time (hr)} \quad \dots(3)$$

$$E_{\text{total}} = E_{\text{pump}} + E_{\text{valve}} + E_{\text{motor}} + E_{\text{arduino}} \quad \dots(4)$$

To calculate the pump's daily energy consumption, the horsepower rating was first converted to watts. This value was then multiplied by the number of operational hours per day, yielding energy consumption in watt-44 using the panel's wattage rating and the average peak sun hours in the area. The total number of panels was derived by dividing the adjusted energy requirement by the output per panel:

$$\text{No of PV Panel} = \frac{\frac{\text{Total Daily Consumption}}{\text{Sun's peak hours}} \times 1.3(\text{constant losses of solar panels})}{\text{Rating of PV}} \quad \dots(5)$$

The result was rounded to the nearest whole number to ensure the system meets daily energy needs.

2.1.3. Charge Controller

The total power output of the solar panel system is calculated by multiplying the number of panels (N_p) by the power rating of each panel (P_r) which is essential for appropriately sizing the charge controller and inverter:

$$T_p = N_p \times P_r \quad \dots(6)$$

To determine the current required for sizing the charge controller, the power law is applied:

$$I = \frac{TP}{V_r} (1.2) \quad \dots(7)$$

where I is current (A), P is total power (W), and V is system voltage (V). Ensuring that the charge controller can handle the maximum expected current prevents overheating and maintains operational safety [13].

Additionally, the charge controller's function includes regulating solar input and managing the charging process of the battery, especially when the battery is in a low state of charge. This helps maximize energy capture and maintain system reliability [13].

2.1.4. Battery

The battery ensures system operation during low or no sunlight and supports continuous power to components such as pumps and sensors. A lead-acid battery was selected for prototyping due to its low cost and availability. It is calculated using:

$$\text{Battery Capacity} = \frac{\text{Total Daily Consumption}}{\text{DOD} \times n \times \text{System Voltage}} \quad \dots(8)$$

Charging time was computed as:

$$\text{Battery Capacity} = \frac{\text{Total Daily Consumption}}{\text{DOD} \times n \times \text{Charging Efficiency}} \quad \dots(9)$$

2.1.5. DC Breaker and Wire

The current required for the system was calculated using the power formula:

$$I_T = \frac{P_w}{V} (125\%) \quad \dots(10)$$

where P is power (W), I is current (A), and V is voltage (V). The result was then multiplied by 1.25 to account for surge currents. This adjusted value was used for sizing the circuit breaker and wire, ensuring safe and reliable operation.

2.2. Design Analysis

This section outlines the system's design and integration process to ensure functionality and alignment with study objectives. As shown in Figure 2, the solar-powered irrigation system uses photovoltaic panels to supply energy to a submersible pump, battery, and control unit (Arduino). The system supports sustainable farming by reducing fossil fuel use and improving water efficiency, though challenges such as high initial cost and weather dependency remain. Figure 2 illustrates a direct solar-powered irrigation setup with integrated soil moisture sensors. The system includes a submersible pump, control unit, and manifolds connected to sprinklers for uniform water distribution. Real-time feedback from soil moisture sensors allows the system to regulate irrigation schedules, optimizing water use and enhancing crop productivity.

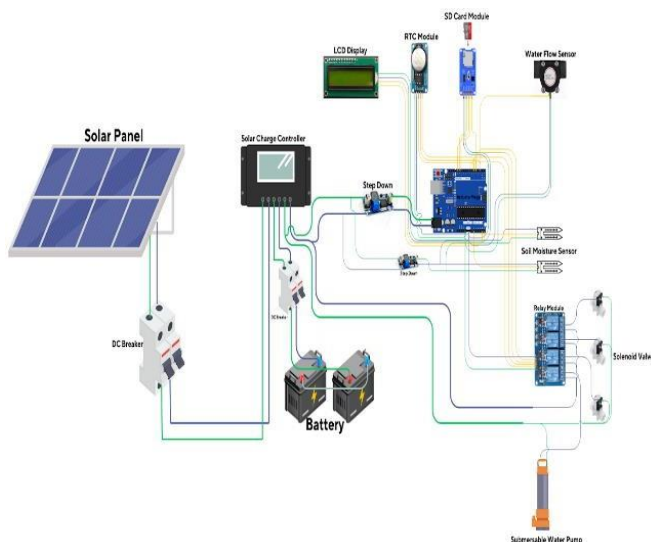


Figure 1

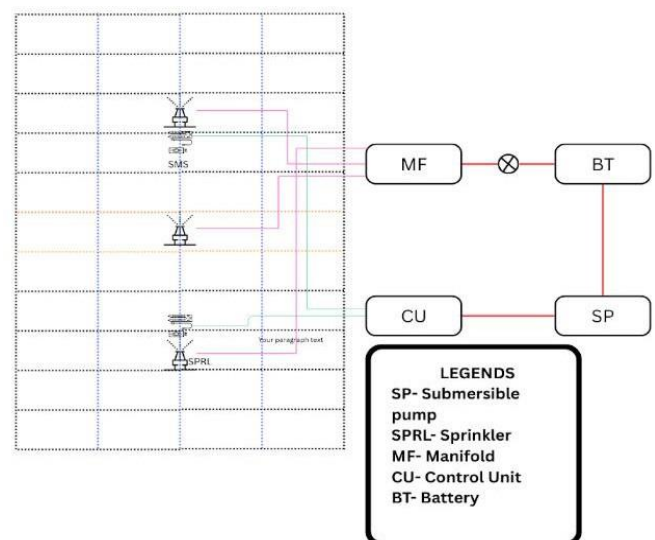


Figure 2

2.3. Testing and Validation

The system was tested to evaluate its ability to generate, store, and utilize sufficient energy for continuous operation. The objective was to confirm whether the solar-powered system could meet the daily energy requirements of components such as the pump, valves, and sensors.

Solar panel performance was observed under varying light conditions to assess its capacity to charge the battery and simultaneously power the system. Battery charge and discharge cycles were monitored to determine storage efficiency and energy availability during low-light periods, such as early mornings and evenings.

Tests were conducted over multiple days, focusing on energy reliability under fluctuating sunlight and irrigation cycles. The results showed that the system operated independently of grid power, confirming its energy autonomy and suitability for off-grid agricultural applications.

2.4. Cost Analysis

The Return on Investment (ROI) was calculated to assess the financial viability of switching from a grid- powered to a solar-powered irrigation system. The formula used is:

$$ROI = \frac{\text{Annual Savings}}{\text{Initial Investment}} (100) \quad \dots(11)$$

Annual savings represent the avoided electricity costs, while the initial investment includes expenses for solar panels, batteries, and installation. To estimate how quickly the investment is recovered, the Payback Period was computed using:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Saving}} \quad \dots(12)$$

These financial metrics provide a clear understanding of the system's cost-effectiveness and support decision-making for solar irrigation adoption in agricultural settings.

3. Results and Discussion

The Energy Consumption of the motor pump needed is based on the computation of rating of the motor multiplied by the number of hours of utilization which resulted in to 3,000 Watt-hour

3.1. Solar Panel and System Performance Analysis

Table 1. Solar Panel and System Performance Analysis

Date	Energy Generated (Whr)	Energy Consumed (Whr)
03-02-25	1428.23	783.02
03-08-25	440.64	354.93
03-15-25	1308.96	770.48
03-22-25	1366.33	764.48
03-29-25	1205.90	765.02
04-05-25	1230.06	781.93
04-12-25	1310.51	728.49
04-19-25	1266.97	1118.40
04-27-25	1262.21	867.55

The data in Table 1 indicates that the solar panel consistently harvested more energy than the system consumed. For instance, on March 2, the system generated 1428.23 Wh while only consuming 783.02 Wh. Even on lower-

generation days like March 8 (440.64 Wh), the consumption remained below generation (354.93 Wh). This trend is consistent across all dates, confirming that the solar energy harvested was sufficient to meet the system's daily load requirements.

Table 2. Daily Battery Operation Status and Charging Recovery Log

May 17				May 18			
Time	Voltage	DOD	CT	Time	Voltage	DOD	CT
7:00:00	24.8	30	2.24	7:00:00	24.5	50	4
8:00:00	24.3	40	3.140	8:00:00	24.8	40	3
9:00:00	24.8	30	2	9:00:00	25	30	2
10:00:00	25.2	10	1	10:00:00	25.3	10	1
11:00:00	25.7	0	-	11:00:00	25.4	0	-
12:00:00	25.7	0	-	12:00:00	25.7	0	-
13:00:00	25.4	10	0.51	13:00:00	25.4	20	1.15
14:00:00	25.7	0	0	14:00:00	25.7	10	0.3
15:00:00	25.7	0	0	15:00:00	25.7	0	-
16:00:40	25.3	80	1.05	16:00:40	25.2	20	1
17:00:00	25.6	10	0.35	17:00:00	25.4	10	0.2
18:00:00	25.6	10	0.35	18:00:00	25.4	10	0.2

The data in Table 2 shows that the battery charges progressively throughout the day, especially during midday when solar exposure is optimal. As indicated by the rising voltage levels and decreasing depth of discharge (DOD), the battery effectively recharges after each usage cycle. This behavior confirms that the system operates under direct sunlight conditions, allowing the battery to recover its full charge after powering the irrigation system.

Table 3. Battery Discharge Cycle

Date	Before V	After V	SOC	Charging Time
May 16	25.7	24.5	50	2.24
May 17	25.4	24.4	50	2.35

Battery discharge data over two consecutive nights showed minimal variation in charging performance. On May 16, the voltage dropped by 0.2 V (25.7 V to 25.5 V) with a 2.24-hour charging time. On May 17, a larger drop of 1.0 V (25.4 V to 24.4 V) was recorded, yet charging time only slightly increased to 2.35 hours. Despite the increased discharge, the State of Charge (SOC) remained at 50%, indicating stable and efficient recharge performance across both cycles.

3.2. Reducing Waste and Improving Resource Use

Water usage comparison in Tabuyuc, Apalit showed that the solar-powered irrigation system consumed an average of 161.2 liters per session, while the traditional method, theoretically estimated using the bucket method, required approximately 1,680 liters per session. This represents a 90.41% reduction in water usage. Over two months, the solar system recorded a total of 9,855 liters, demonstrating consistent, efficient, and crop- responsive irrigation through automated control.

3.3. Integration of Soil Moisture Sensor

A paired t-test revealed a statistically significant difference ($p = 0.01$) in average soil moisture between the Traditional Irrigation System (TIS) in Porac, Pampanga and the Solar-Powered Irrigation System (SPIS) in Apalit, Pampanga. The TIS recorded a higher mean value of 59.33, while the SPIS showed a lower mean of 49.91, indicating more efficient water use under solar-powered operation.

The lower moisture levels under SPIS reflect controlled and sufficient irrigation with reduced water input. In contrast, the TIS in Porac suggests excessive water use, which may lead to waste. These results support the SPIS as a more efficient and sustainable method for managing water in agriculture, particularly in areas where water conservation is critical.

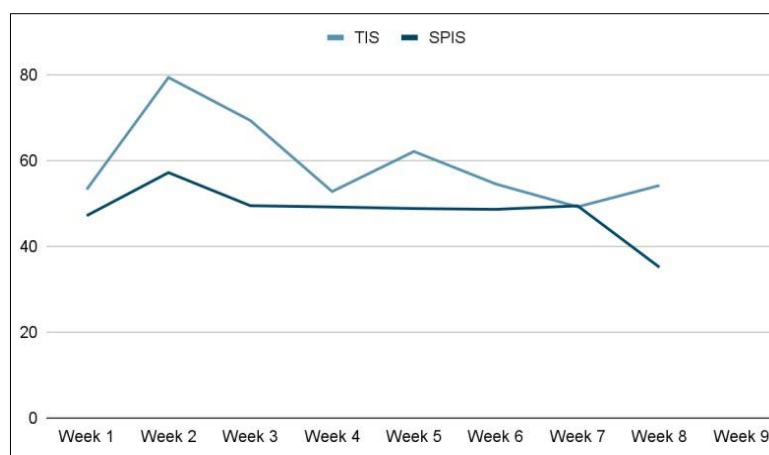


Figure 3. Average Soil Moisture

3.4. Economic Assessment of Electricity Savings

The solar-powered irrigation system achieved full energy independence, eliminating reliance on grid electricity. Based on a theoretical estimate of local grid consumption (3.5 hours/day at ₱11.0944/kWh), this translates to a monthly savings of approximately ₱1,260. With an initial cost of ₱28,231, the estimated payback period is 1.8 years.

This short return period, combined with off-grid functionality, highlights the system's viability for rural deployment. Beyond cost savings, it also contributes to sustainable energy use by reducing carbon emissions and ensuring uninterrupted irrigation.

4. Conclusion

This study confirmed the technical adequacy, cost-efficiency, and sustainability of the 300W solar-powered irrigation system (SPIS) implemented in Tabuyuc, Apalit, Pampanga. Comprising a 300W solar panel, a 24V 50 Ah lead-acid battery, and an automated soil moisture sensor, the system demonstrated reliable performance across multiple operating days. Energy generation ranged from 440.64 Wh to 1366.33 Wh, effectively responding to fluctuating solar irradiance and irrigation demands. On April 19, the system delivered 1118.40 Wh during peak water use, indicating operational integrity under load. Voltage recovery after deep discharge and consistent charging cycles—2.24 hours on May 16 and 3.14 hours on May 17—affirmed the system's efficiency and the

controller's adaptability.

Water conservation was a significant achievement, with only 161.2 liters used per irrigation session—over 90% less than the 1,680 liters typically consumed using traditional methods. The automated control reduced both water wastage and labor demands. Financial analysis showed a monthly electricity savings of approximately ₱1,260, leading to a payback period of around 1.8 years for the ₱28,231 investment. After this period, continued operational savings reinforce its cost-effectiveness. Overall, the SPIS demonstrated stable off-grid power supply, efficient water usage, and economic viability, supporting its potential for scalable deployment in rural agricultural settings.

5. Recommendations

1. It is recommended to upgrade the battery capacity to 100 Ah or more in order to allow longer irrigation operations, especially during extended cloudy weather or night-time use.
2. The installation of multiple soil moisture sensors in various parts of the field is advised to improve the accuracy of irrigation, particularly in larger or uneven farm areas.
3. Long-term field testing under different environmental and weather conditions should be conducted to assess the durability and performance of the system over time.
4. Collaborations with government and non-government agricultural programs are encouraged to promote wider adoption of the system and provide possible funding or technical support to farmers.
5. Lastly, it is suggested to develop modular and scalable versions of the system to accommodate various crop types and farm sizes, making the technology adaptable for broader agricultural use.

Declarations

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This study did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors declare no competing financial, professional, or personal interests.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

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